Inferring Galactic interstellar extinction with Gaia

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with inputs from
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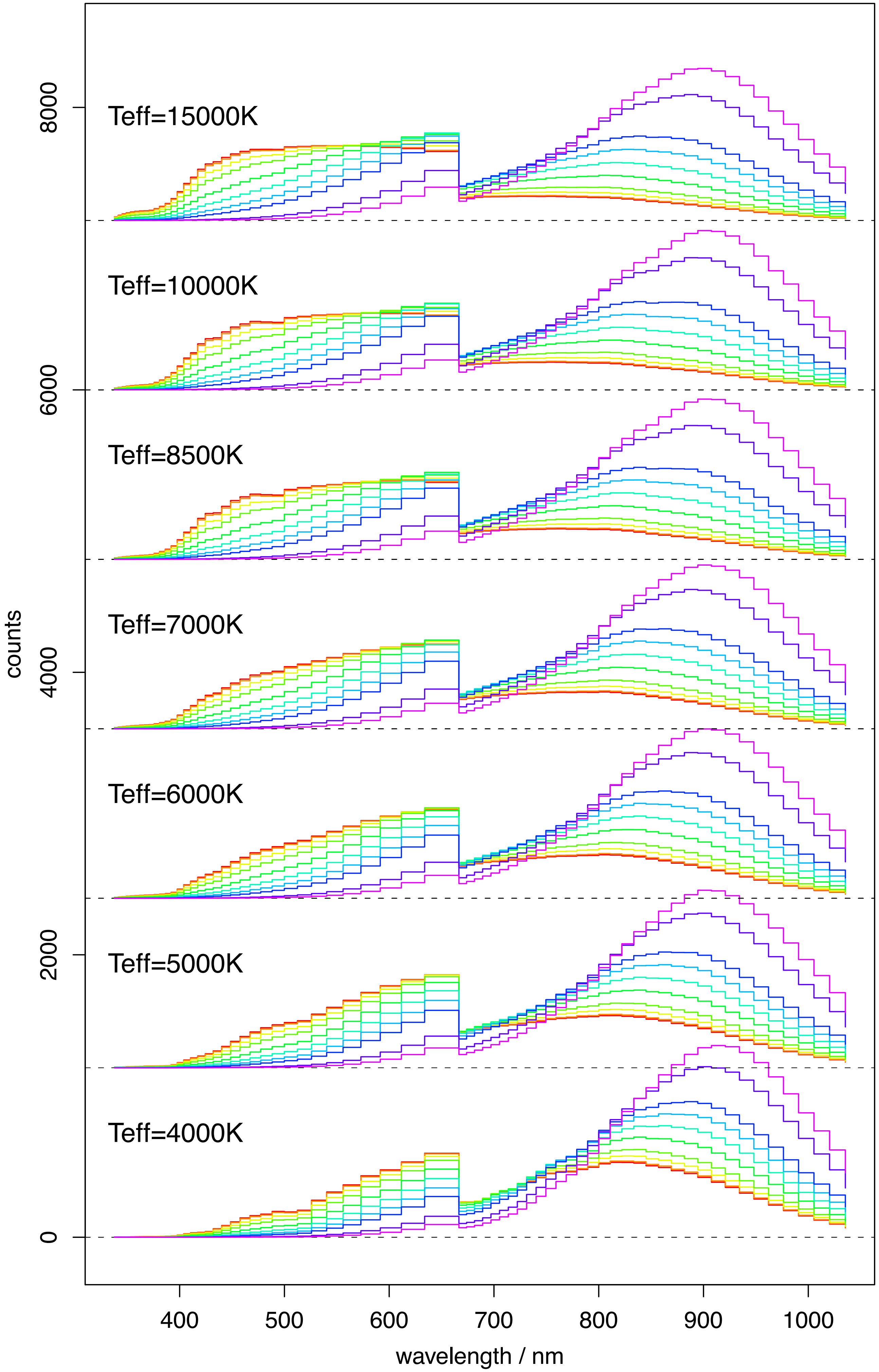
Outline

- Extinction estimation in Gaia DPAC (CU8)
    - star-by-star with GSP-Phot package (3 methods)
    - mean total extinction over a field with TGE package
- 3D extinction with Gaia data
    - idea of joint inference

Coryn Bailer-Jones is manager of
DPAC CU8 "Astrophysical Parameters"
(but not only...!)

Generalized Stellar Parametrizer (GSP-Phot)

- Purpose: Estimate the intrinsic stellar parameters (T_{eff}, logg, [Fe/H], [α/Fe]) and line-of-sight extinction parameters (A_0, R_0) for individual stars ("Astrophysical Parameters" = APs)
- Extinction law $A_\lambda = A_0[a_\lambda + b_\lambda / R_0]$
- Uses primarily the BP/RP spectra from Gaia
- Three algorithms
  - Support Vector Machine (inverse mapping)
  - ILIUM (iterative local method using forward modelling)
  - q-method (Bayesian method), can also use the parallax
- All fit ("trained") using synthetic/semi-empirical libraries



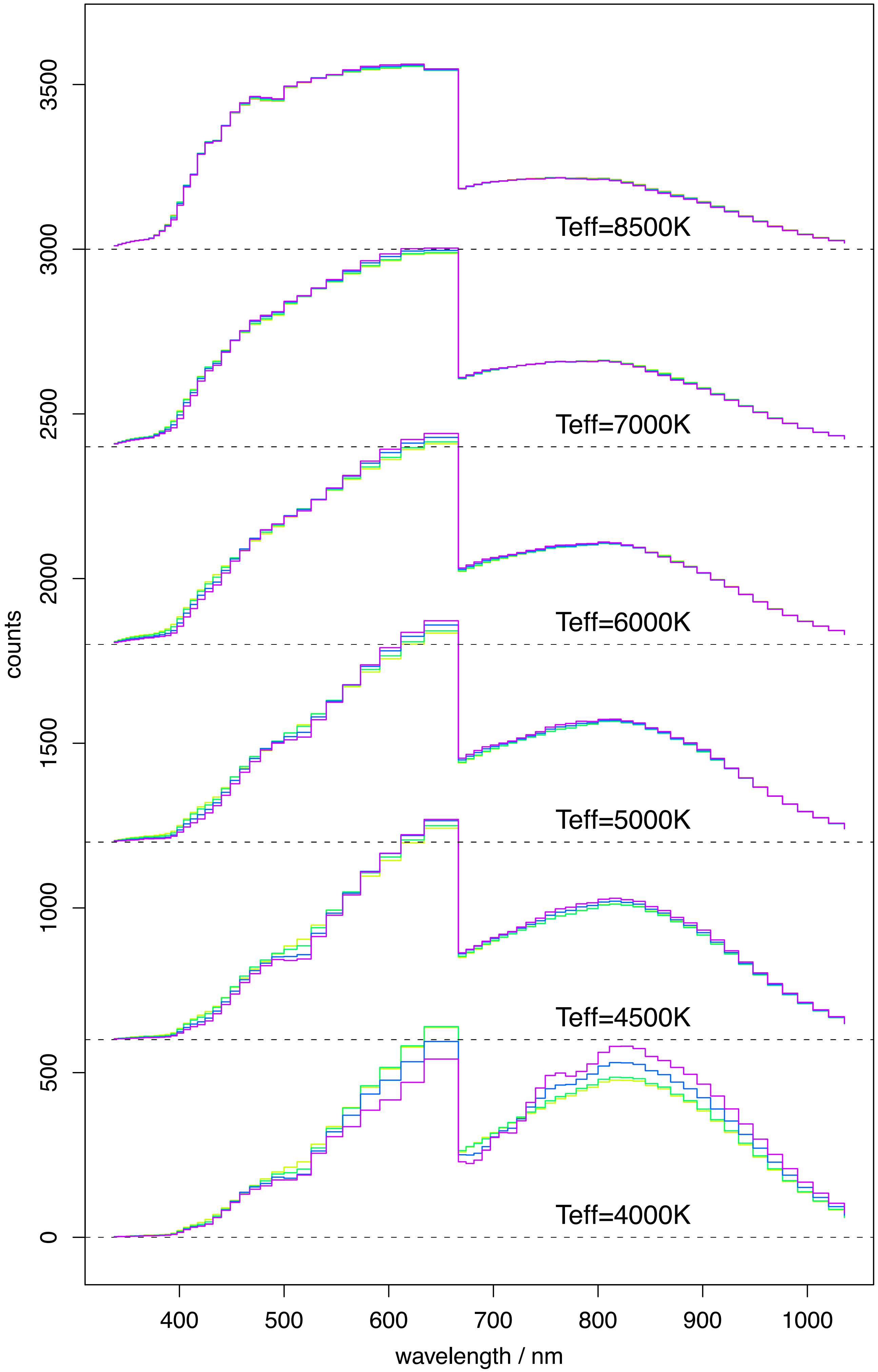
Gaia BP/RP spectrophotmetry of synthetic stellar spectra

T_{eff} and A_0 variation

A_0 = 0, 0.1, 0.5, 1, 2, 3, 4, 5, 8, 10

(R_0=3.1)

T_{eff} and A_0 are “strong” APs



Gaia BP/RP spectrophotmetry of synthetic stellar spectra

T_{eff} and [Fe/H] variation

[Fe/H] = -3, -2, -1, 0, +0.5

(A_0=0, logg=4)

[Fe/H] is a "weak" AP

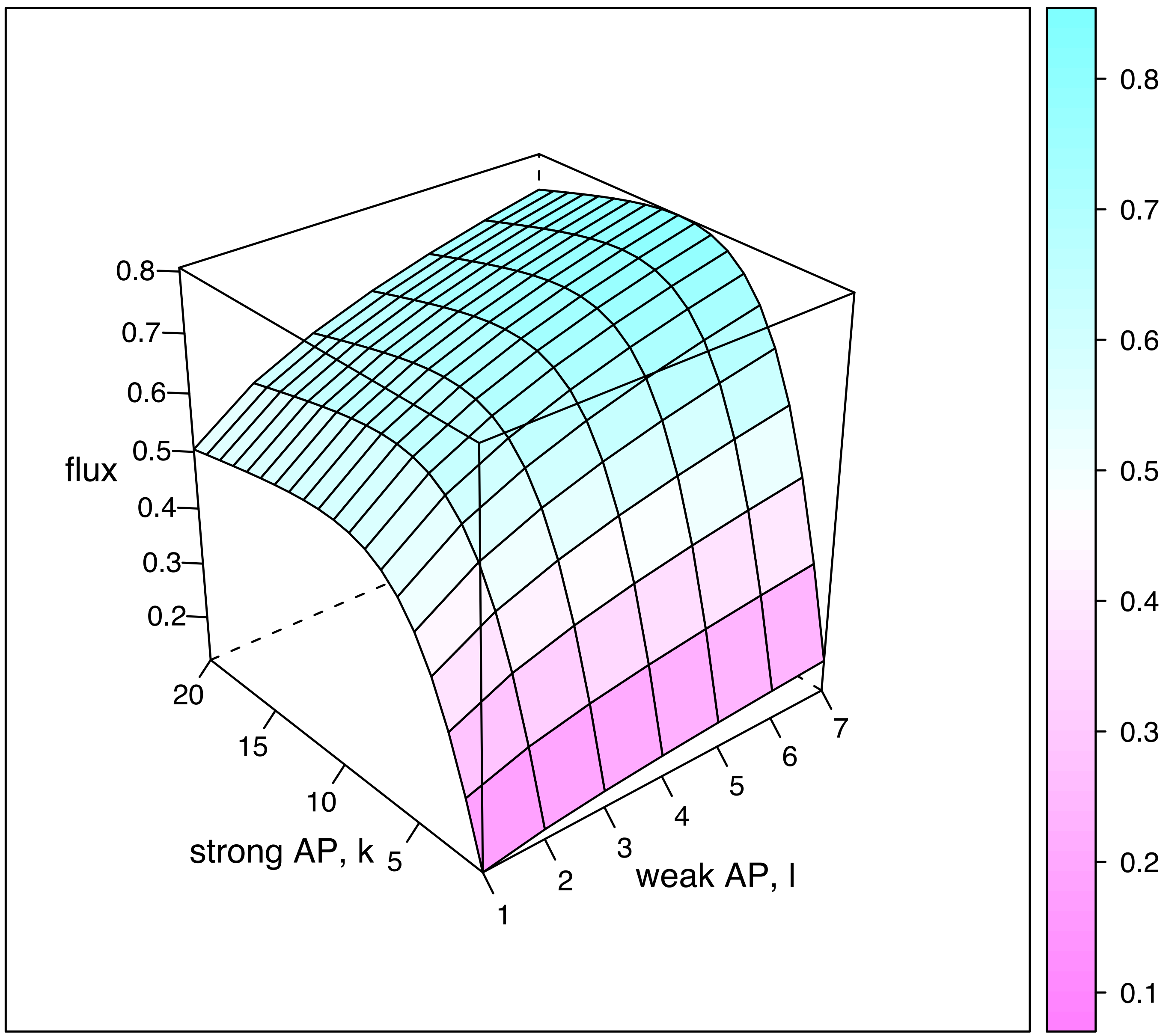
Support Vector Machine

- Off-the-shelf machine learning method
- Learns an explicit mapping between spectrum and APs
- Some results for a synthetic library with T_{eff}=3000 to 10 000K, $A_0 \leq 10$ mag, wide range of logg and [Fe/H] (end-of-mission):

AP residual	G mag	All stars	A stars	F stars	G stars	K stars
$<\|Teff(true) - Teff(est)\|>$(K)	<16.5	71	111	65	53	117
$<\|A0(true) - A0(est)\|>$(mag)	<16.5	0.05	0.05	0.03	0.04	0.13
$<\|FeH(true) - FeH(est)\|>$(dex)	<16.5	0.33	0.65	0.35	0.23	0.32
$<\|LogG(true) - LogG(est)\|>$(dex)	<16.5	0.39	0.23	0.27	0.43	0.90
$<\|Teff(true) - Teff(est)\|>$(K)	>16.5	265	426	226	226	392
$<\|A0(true) - A0(est)\|>$(mag)	>16.5	0.14	0.16	0.11	0.14	0.30
$<\|FeH(true) - FeH(est)\|>$(dex)	>16.5	0.51	0.71	0.51	0.41	0.58
$<\|LogG(true) - LogG(est)\|>$(dex)	>16.5	0.47	0.35	0.33	0.51	1.02

Forward modelling

- For each band (pixel) i, fit a smooth forward model for flux: $p_i = f_i(\boldsymbol{\phi})$ where $\boldsymbol{\phi} = (\phi_1, \phi_2, \phi_3, ..., \phi_j)$ are the APs
- gradients are the "sensitivities": $s_{ij} = \partial p_i / \partial \phi_j$



Flux variation in *one* band (pixel) as a function of the APs

ILIUM

- ILIUM uses the forward model to search locally for the solution (best fitting APs) using a Newton-Raphson iterative method

$$\delta \boldsymbol{p} = \mathbf{S}\,\delta\boldsymbol{\phi}$$

$$\delta\boldsymbol{\phi} = (\mathbf{S}^T\mathbf{S})^{-1}\mathbf{S}^T\,\delta\boldsymbol{p}$$

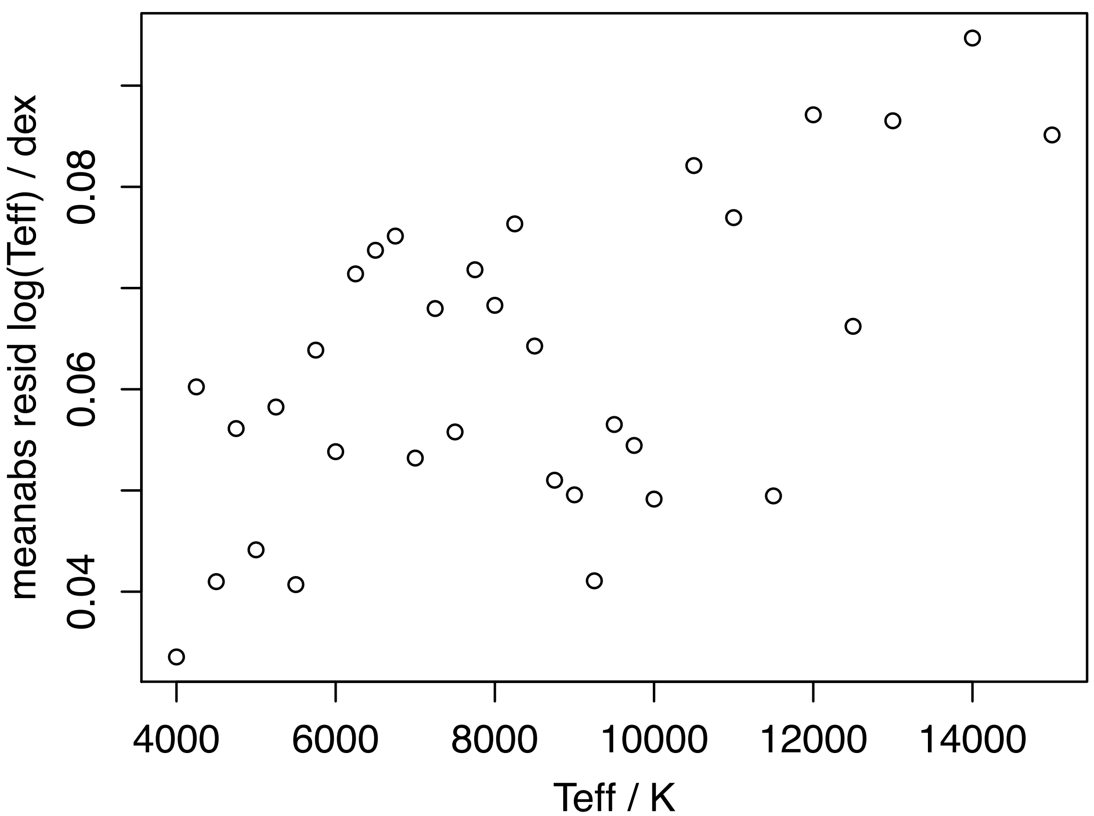
$\mathbf{S}$ is the sensitivity matrix

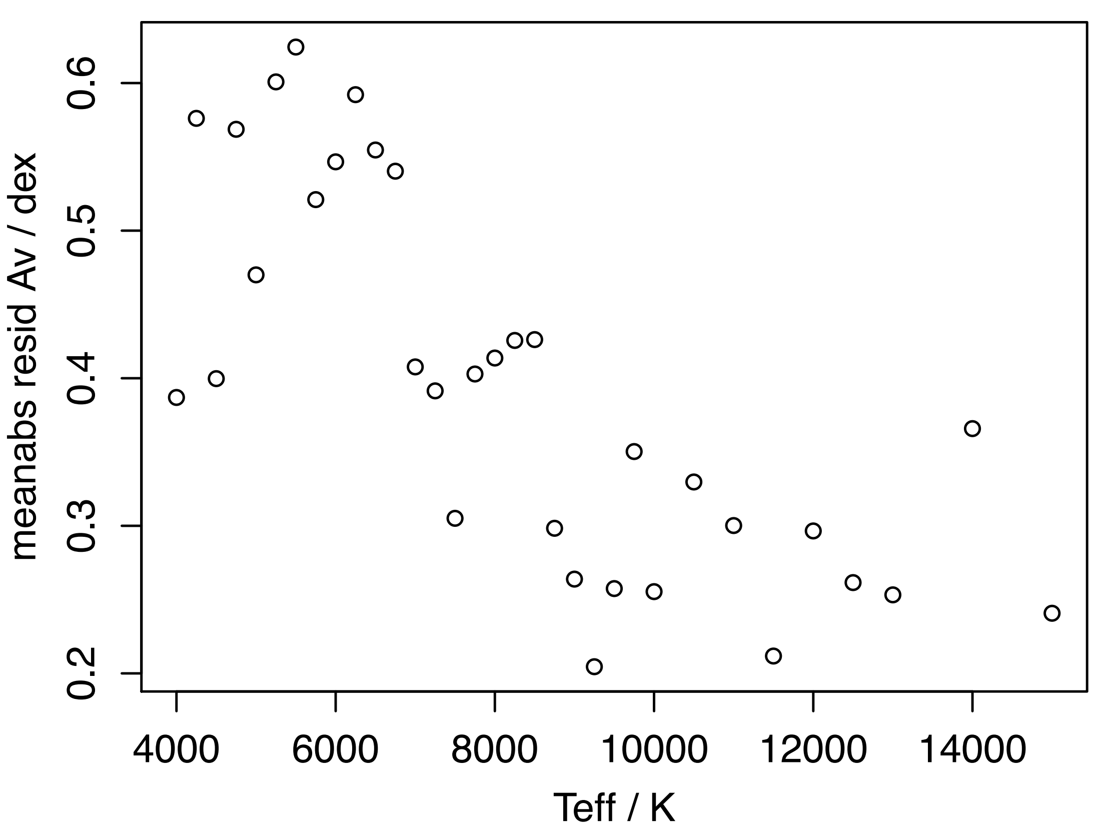
  - a band's contribution is weighed by its sensitivity to each AP
  - gives uncertainty estimates: covariance matrix for the estimated APs

$$\mathbf{C}_\phi = (\mathbf{S}^T\mathbf{S})^{-1}\mathbf{S}^T\mathbf{C}_p\mathbf{S}(\mathbf{S}^T\mathbf{S})^{-1}$$

- see Bailer-Jones 2010 (MNRAS 403, 96) for full details plus more results (but more optimization required for Gaia...)

Example ILIUM performance on T_{eff}, A_0, logg





Model applied to estimate 3 APs with prior range (solar metallicity):

T_{eff}: 4000 to 15 000 K
A_0: 0 to 10 mag
logg: -0.5 to 5.0 dex

Mean absolute errors:

$\log(T_{eff})$	A_0	logg	
0.013	0.072	0.29	G=15
0.061	0.30	1.10	G=18.5

Plot:
Residuals vs. T_{eff} at G=18.5

q-method

- Uses photometry (e.g. BP/RP), parallax and apparent mag
- Bayesian method to infer PDF over APs given data, $P(\phi|\mathbf{p}, q)$

  where $q = M + 5\log\varpi = m + A_0 - 5$

  is a measured (noisy) quantity. M and m are absolute and apparent magnitude, ϖ is parallax. $\mathbf{p}$ is (spectro)photometry
- See Bailer-Jones 2011 (MNRAS 411, 435) for full details
- Adopt a Gaussian likelihood (noise) model for $\mathbf{p}$

$$P(\boldsymbol{p}|\phi) \propto e^{-D^2/2} = \exp\left(-\frac{1}{2}[\boldsymbol{p} - \boldsymbol{f}(\phi)]^T \mathbf{C}_p^{-1} [\boldsymbol{p} - \boldsymbol{f}(\phi)]\right)$$

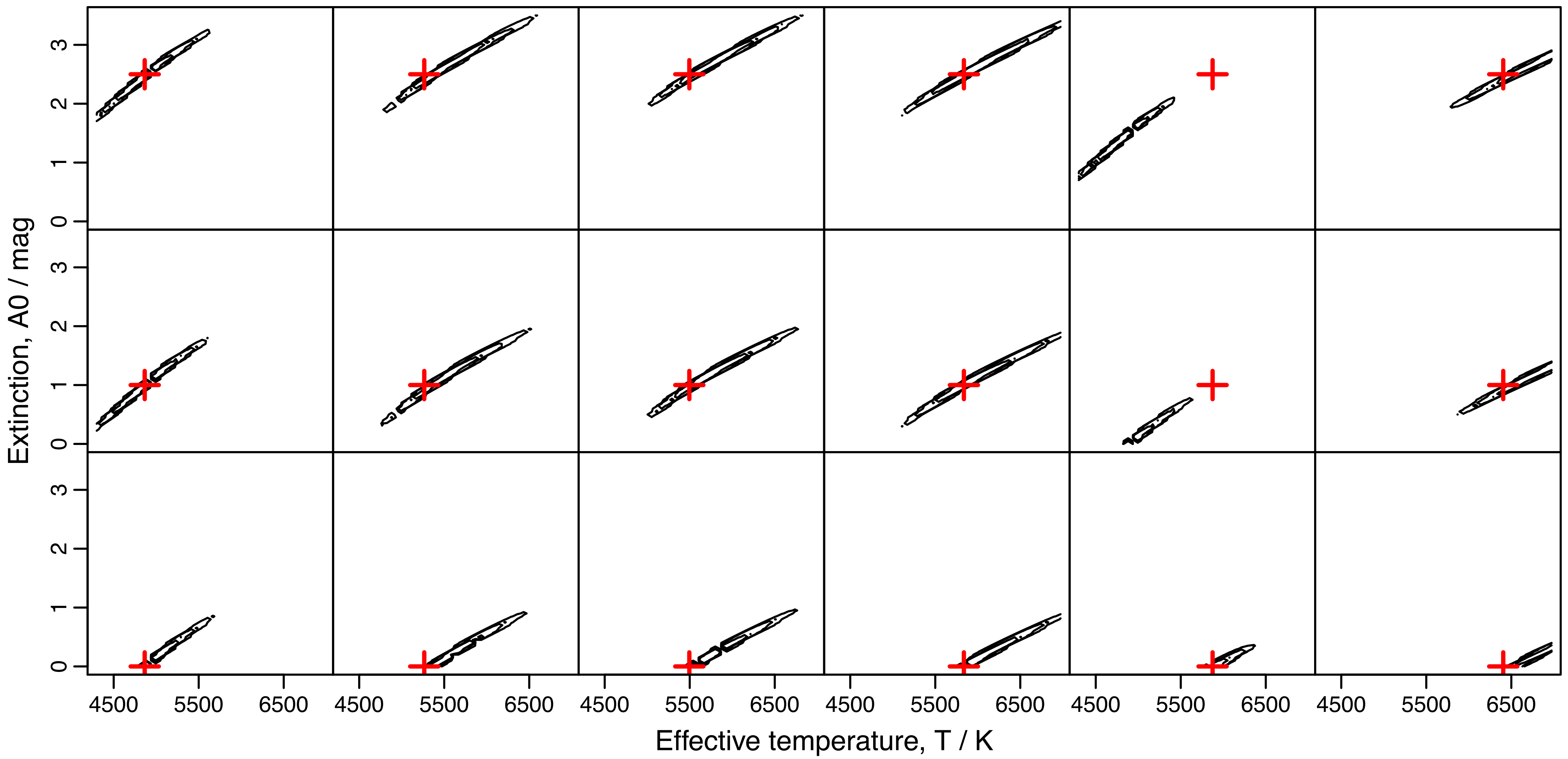
forward model

data covariance

q-method demonstration

- Infer T_{eff} and A_0 using BVJHK photometry and Hipparcos parallaxes for ~85 000 2MASS/Hipparcos stars
- True APs for forward model fitting (training data):
    - T_{eff} from Valenti & Fischer (2005) from high-res. spectroscopy
    - artificially reddened to give A_0 variance
    - 5280 stars with T_{eff} = 4700-6600, A_0 = 0-2.5mag

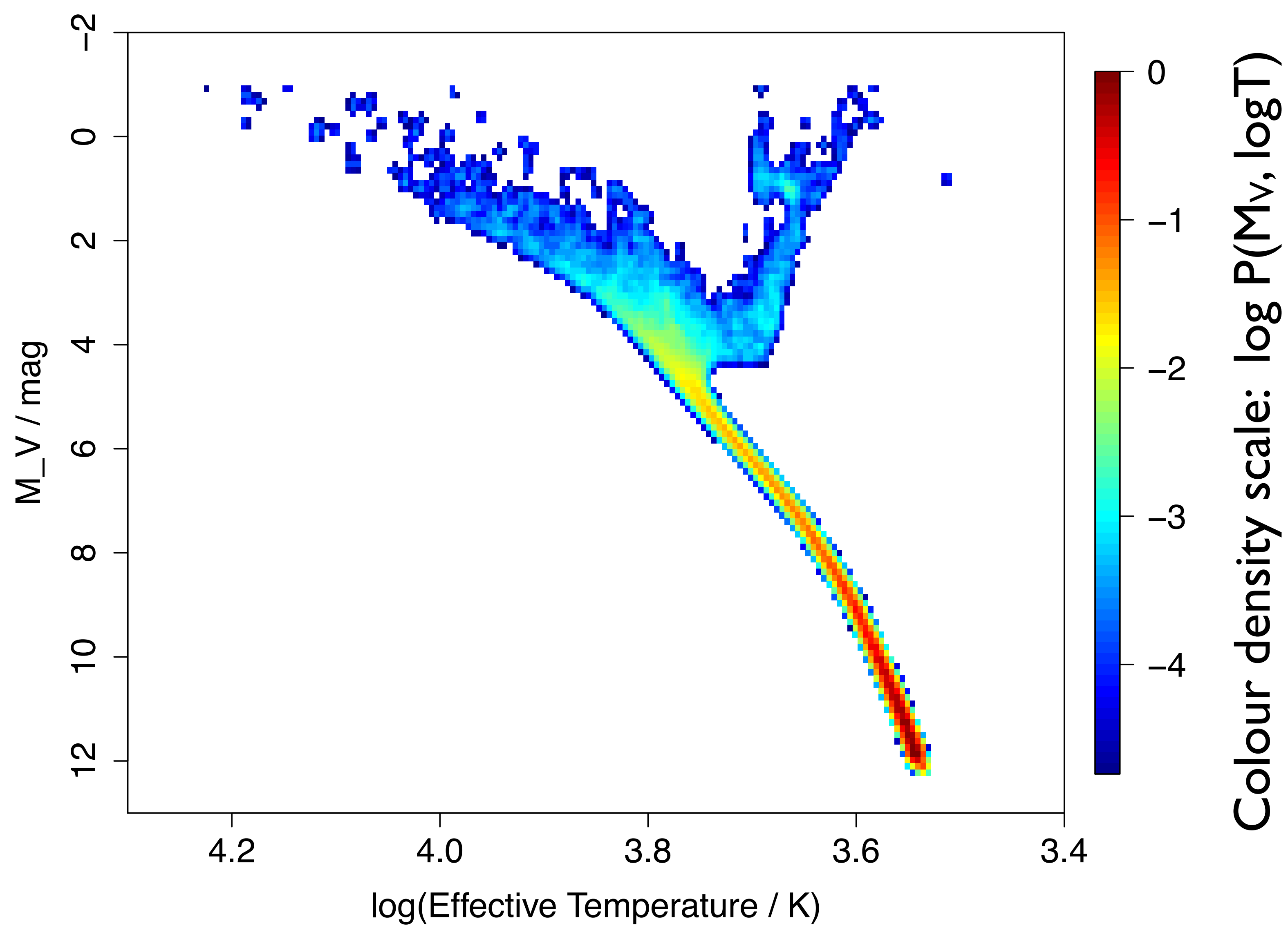
AP estimation from BVJHK colours (only)



- "true" APs shown as red cross
- contours enclose 90%, 99% and 99.9% of posterior probability $P(\phi|\mathbf{p})$
- note the significant degeneracy between T_{eff} and A_0

Information beyond the spectrum

- Spectrum: p constrains T_{eff} and A_V
- Parallax and apparent magnitude: q constrains $M_V + A_V$
- HRD ("prior") constrains M_V and T_{eff}



Probabilistic inference

Combine all the data probabilistically:

$$P(A_0, T|\boldsymbol{p}, q) = \frac{P(\boldsymbol{p}, q|A_0, T)P(A_0, T)}{P(\boldsymbol{p}, q)}$$

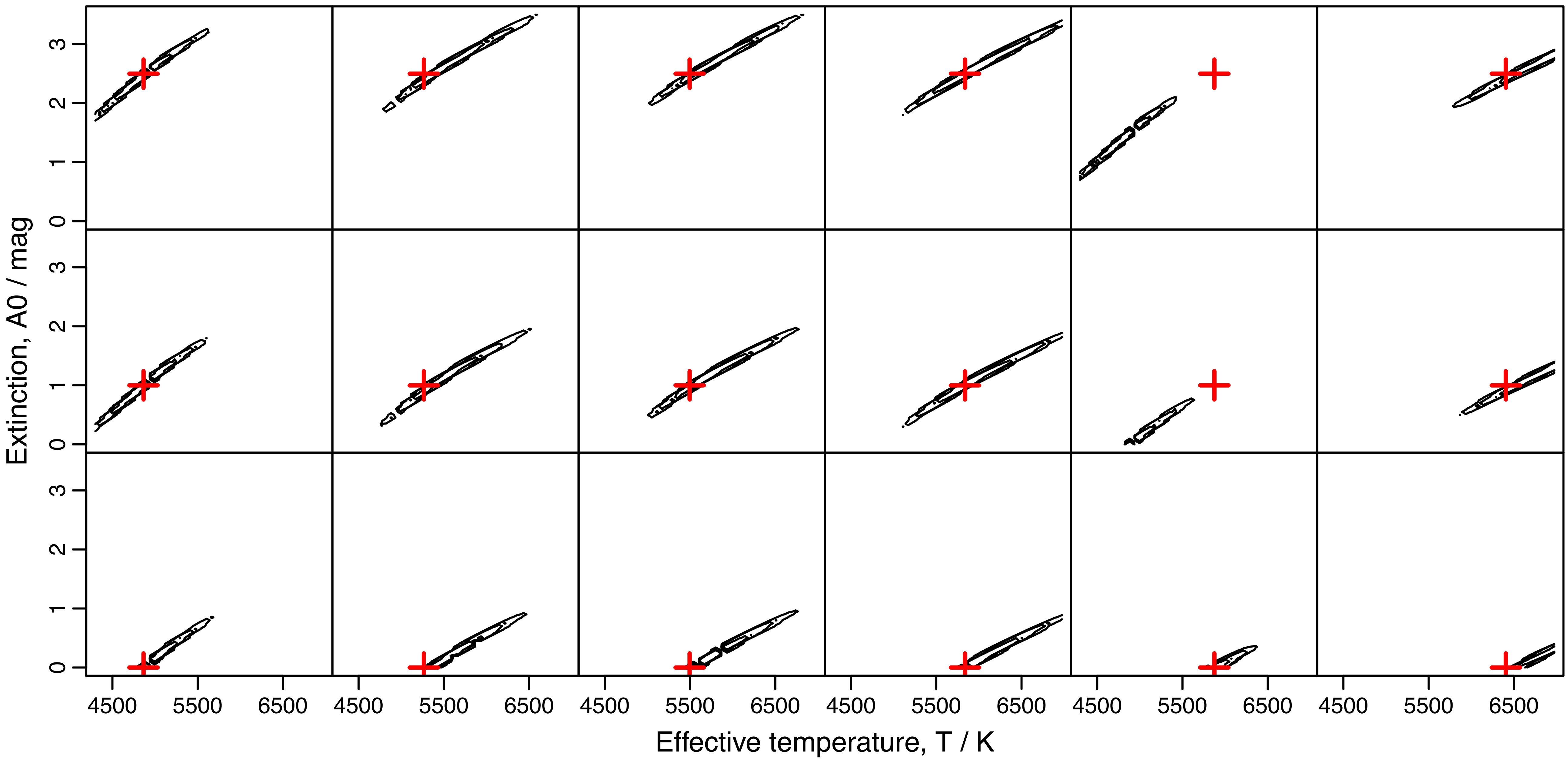
Bayes' theorem

$$= \underbrace{P(\boldsymbol{p}|A_0, T)}_{\text{likelihood}} \underbrace{\frac{P(A_0)}{P(\boldsymbol{p}, q)}}_{\text{priors}} \underbrace{\int_{M_V} \underbrace{P(q|M_V, A_0, T)}_{q \text{ constraint}} \underbrace{P(M_V, T)}_{\text{HRD prior}} dM_V}_{\text{HRD/q factor}}$$

colour-only estimation

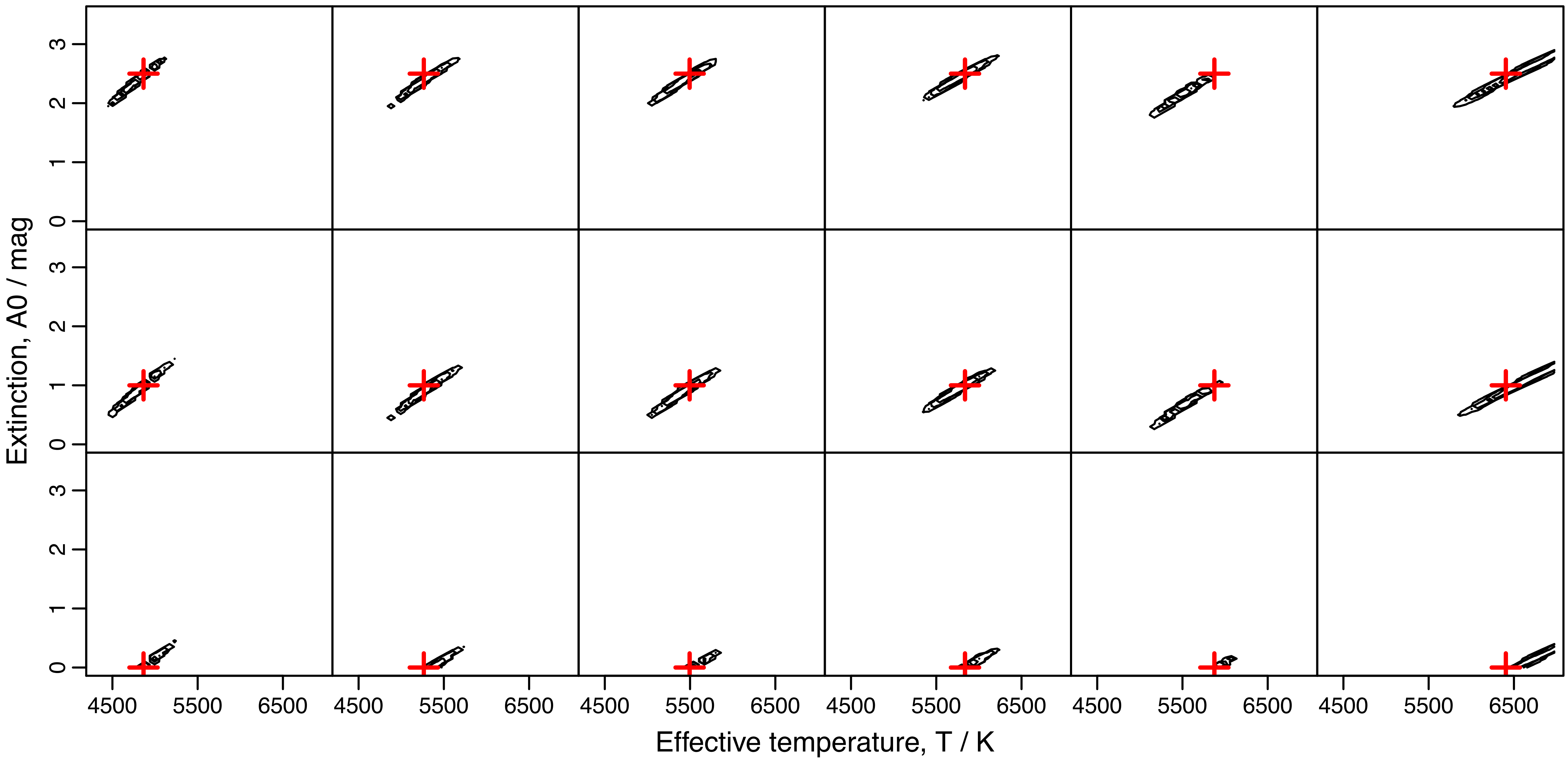
AP estimation from BVJHK colours

$$P(\phi|\mathbf{p})$$



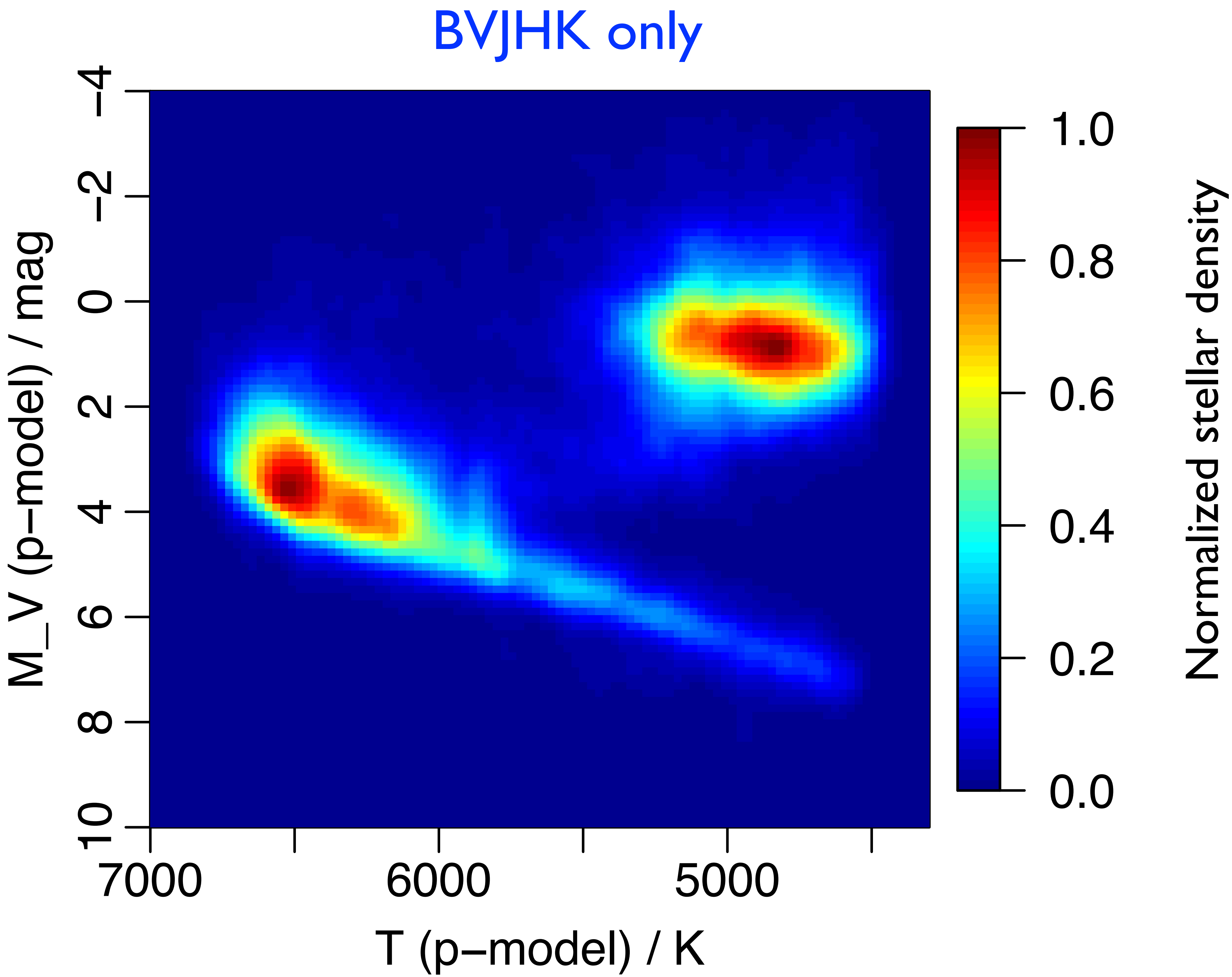
AP estimation from BVJHK colours + q, HRD

$$P(\phi|\mathbf{p}, q)$$

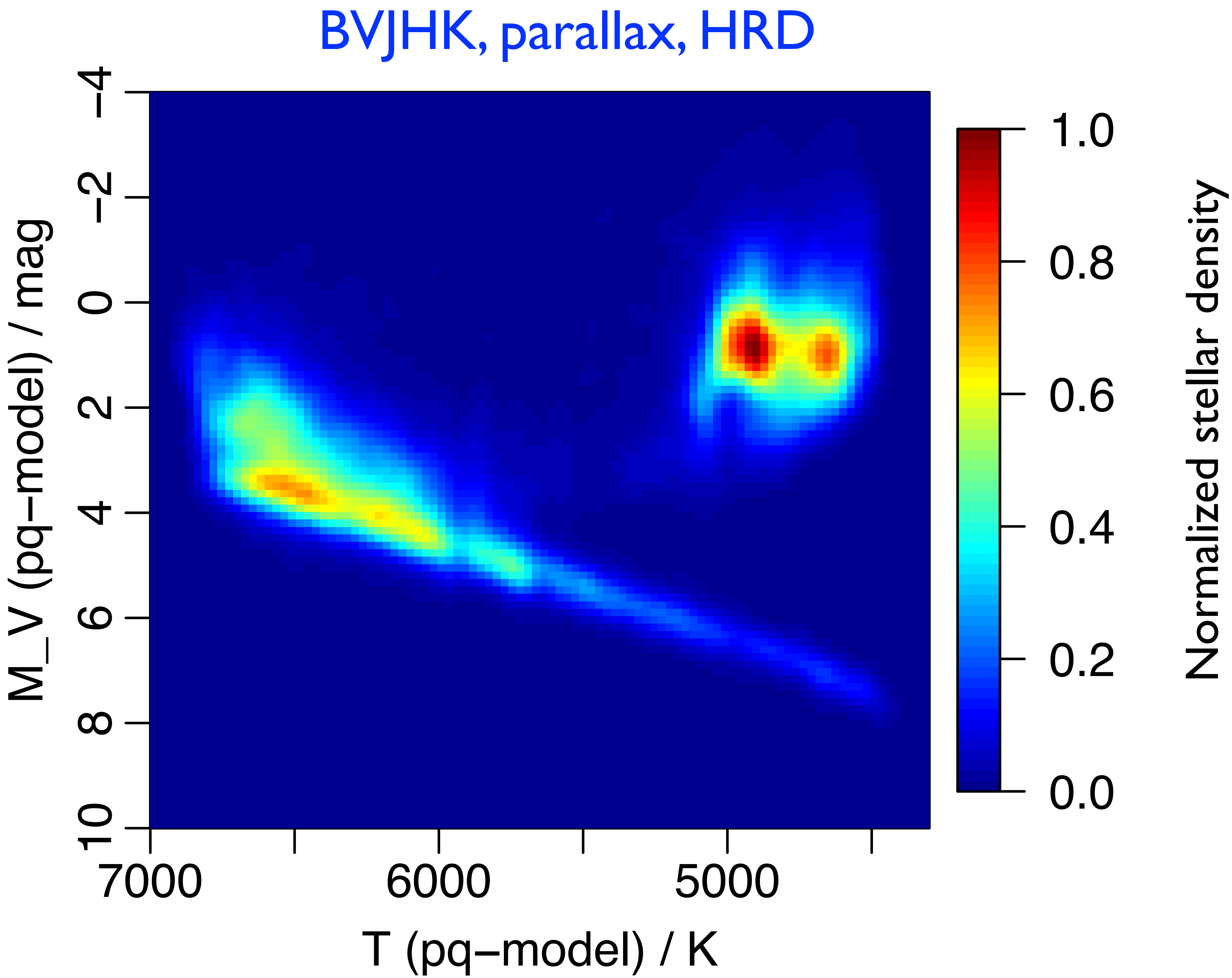


- Accuracy ~40% higher: Mean abs. errors 0.015dex in log(T_{eff}) and 0.2 mag in A_0
- Improved precision (contours more compact)

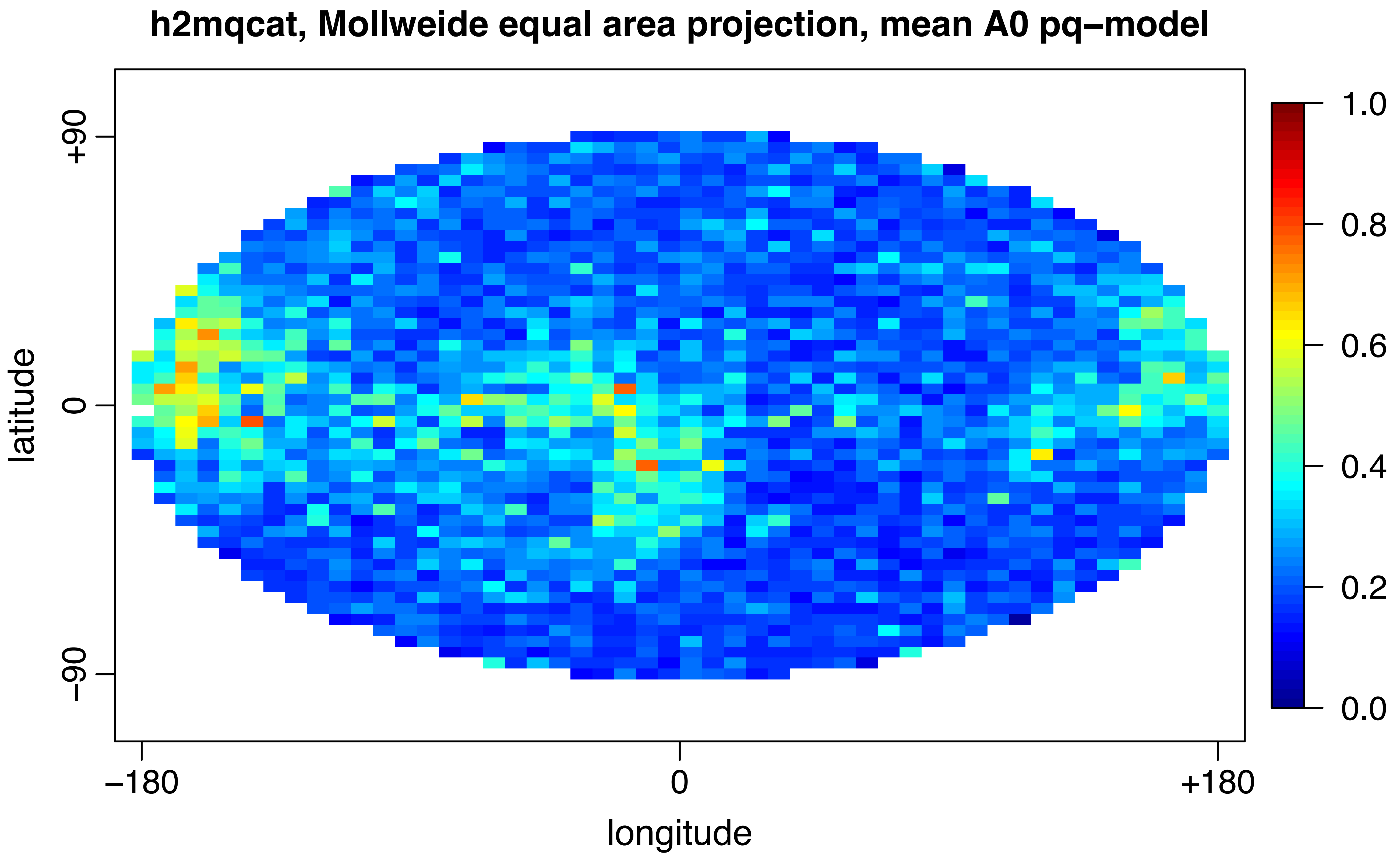
Application to 85 000 Hipparcos/2MASS stars



Application to 85 000 Hipparcos/2MASS stars



Derived extinction map



Summary of Gaia AP estimation with GSP-Phot

- There is a significant, *intrinisic* T_{eff}-A_0 degeneracy
- AP estimates to take advantage of parallax, apparent magnitude and constraints imposed by physics (i.e. HRD prior)
- Gaia catalogue will provide
  - multiple AP estimates (i.e. from each method)
  - posterior PDF from q-method in some cases (perhaps summarized as a covariance matrix where appropriate)
  - APs estimated by other algorithms in CU8 dedicated to specific stars (e.g. emission line stars, very cool stars), and use of the high resolution RVS spectra (for brighter stars)
- DPAC TN summarizing performance (CHL-005) due soon!

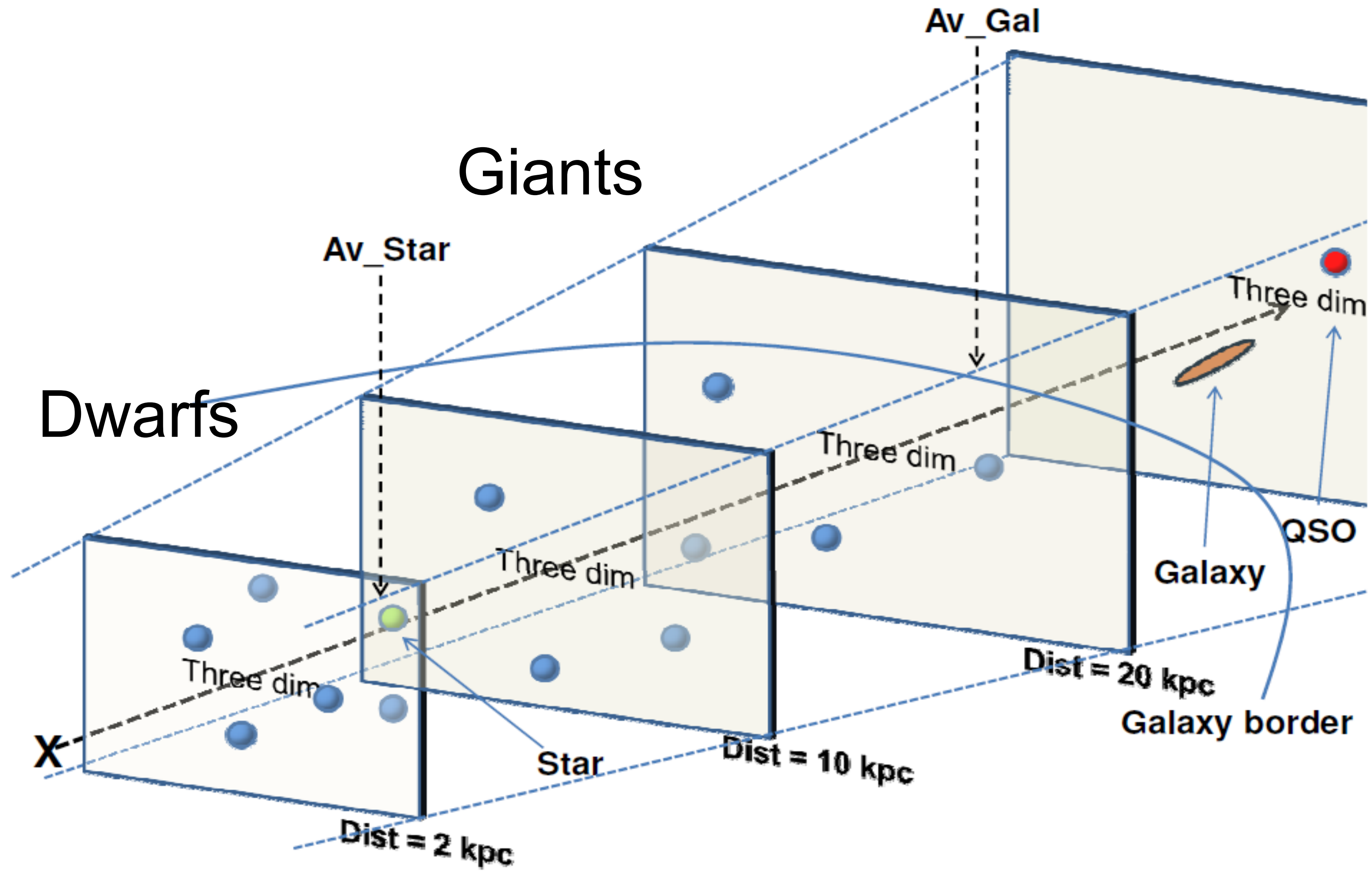
Total Galactic Extinction (TGE)

- Role: estimate integrated extinction to the edge of our Galaxy in a field
  - using the single star extinction estimates in that field from GSP-Phot
- Purpose: provide input extinction for estimating the APs of extragalactic others, especially quasars
- Objectives
  - provide an all-sky HEALpix-based total Galactic extinction map
  - estimate both extinction parameters, A_0 and R_0

Total Galactic Extinction (TGE)

Inputs for TGE are:

T_{eff}, A_0, logg (from GSP-Phot) and parallax, for individual stars



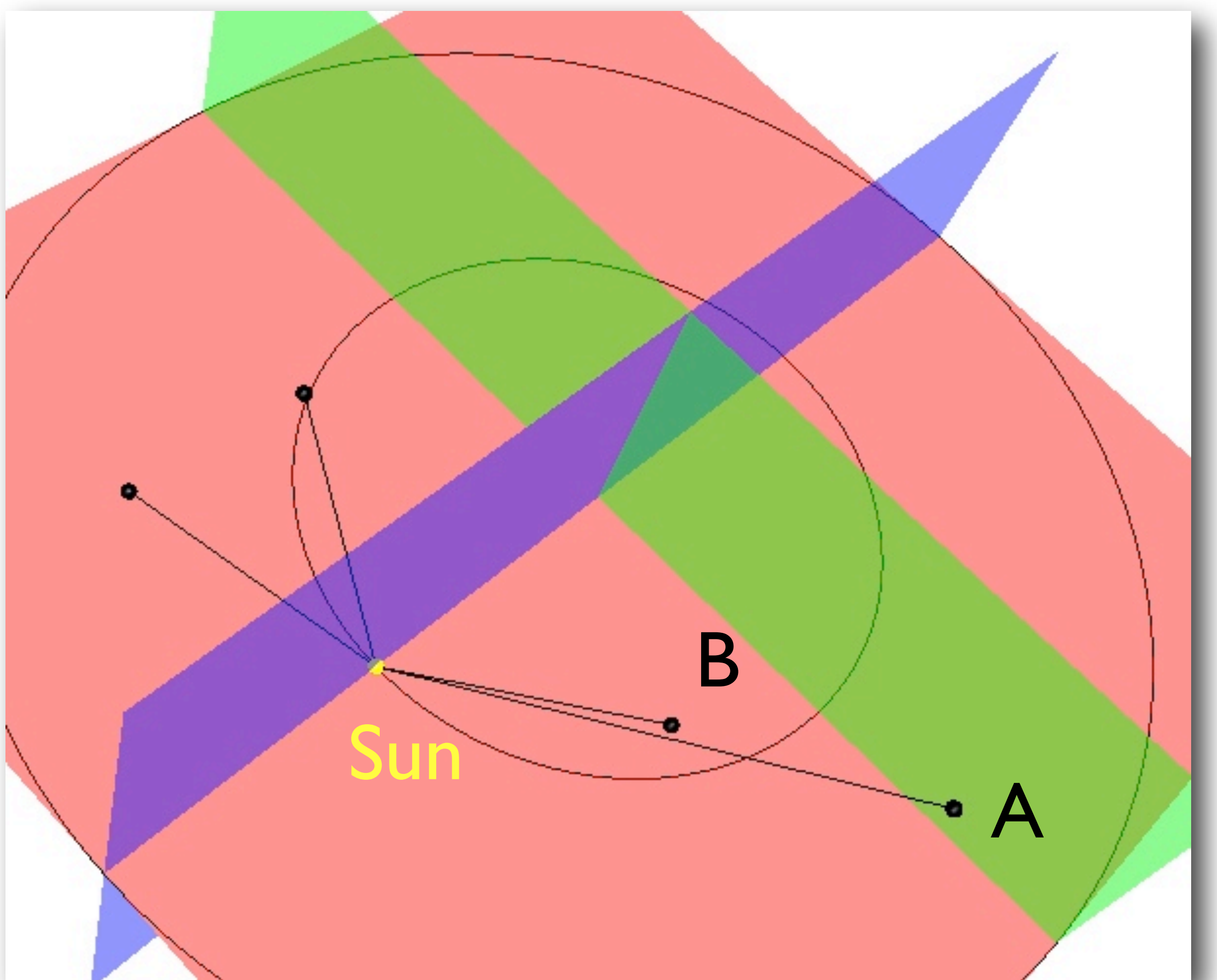
- Solid angle calculation uses the HEALpix
- Extinction tracers selected according to their estimated APs T_{eff} and logg
- Use distant extinction tracers (selected on parallax) to estimate the Total Galactic Extinction for a given HEALPix

Total Galactic Extinction (TGE)

- Software package in place and being tested (see HLI-005)
- Future developments
  - additional selection criteria, including uncertainty in input APs, [Fe/H], variability
  - investigate accuracy of R_0 estimation per HEALpix
  - provision of extinction map with variable resolution (HEALpix levels 6, 7, ...)

3D extinction estimation

- GSP-Phot extinction estimates combined with l,b,ϖ allow us to construct a 3D extinction map
- But as it's star-by-star, it does not respect "obvious" constraints, e.g. A_0 increasing with distance at fixed l,b (this is a prior)



Star A should probably have a higher extinction than star B in general

Joint modelling of extinction for N stars

- Introduce mutual constraints on individual extinctions
  - e.g. a smooth variation of A_0 in 3D space
- Parametrize spatial variation of A_0, e.g. $A_0 = f(l, b, \varpi \, ; \mathbf{a})$
- infer $P(\{T_{\mathrm{eff}}, A_0, \ldots\}, \mathbf{a} \mid \{\mathbf{p}, q\})$ where {} represents the N stars
  - posterior is over a very high dimensional parameter space, $O(N)$!
  - marginalize to get $P(\{A_0\} \mid \{\mathbf{p}, q\})$

Gaia on interstellar extinction: Summary

- Gaia catalogue will have individual star extinction estimates derived from BP/RP spectrum
  - three methods, one of which also uses parallax and HRD (GSP-Phot)
  - significant, *intrinsic* T_{eff}-A_0 degeneracy (reduced by using parallax/HRD)
  - catalogue provides uncertainty estimates and posterior PDFs
  - combined over small field to provide total extinction; used as inputs by quasar and galaxy AP estimation algorithms in DPAC
- Approximate A_0/mag accuracy (mean abs.; end-of-mission) for broad (0-10) prior range
  - 0.1 at G=15; 0.3 at G=18.5 [ILIUM]
  - 0.05 for G<16.5; 0.15 for G=16.5 to 20 [SVM]

Work still in progress...feedback welcome!

- How appropriate is the extinction law? (Grey extinction?)
- How many extinction parameters can we estimate with Gaia?
- What are suitable priors for 3D modelling?
  - not all extinction variation is smooth! use multi-scale?
- How should we best combine with non-Gaia data?
- Questions, suggestions and comments very welcome:
  - Coryn Bailer-Jones, calj@mpia.de
  - This presentation on line at www.bailer-jones.de
- Thanks to Anthony Brown for giving this talk!